Structural Modeling of Tesla TDR Positron Target

W. Stein, J. C. Sheppard

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Werner Stein[1]
John C. Sheppard[11]

ABSTRACT

The Tesla positron target is a 0.4 radiation length thick titanium target that is rotating with a speed of 50 m/s at its periphery. Energy deposition from one pulse occurs over 1 millisecond and results in heating of the target over a 5 cm arc of material. The 22.2 MeV photon beam has a spot size of 0.75 mm and results in a maximum temperature jump of 440 °C. Stresses are induced in the material from thermal expansion of the hotter material. Peak effective stresses reach 38 Ksi (2.7×10^8 Pa), which is lower than the typical yield strength of a titanium alloy by a factor of about 3.

INTRODUCTION

The next generation of linear colliders require positron beams at greater intensities than in previous collider designs. The Tesla design[1] utilizes a wiggler to generate a high energy photon beam. A thin titanium target (0.4 radiation length) placed in the path of the beam is used to convert the photons into positrons.

Peak shock stresses in the target and energy dissipation are major considerations in the design of the target. Due to the relatively slow energy deposition (1 ms/pulse), shock analyses show that a quasi-static thermal stress analyses is adequate for this design.

To avoid excessive heating and to reduce thermal stresses in the target, the target is rotated to spread the beam energy deposition over a larger region of the target. The beam pulses occur 5 times per second and the design goal is to rotate the target to maximize the time before beam pulses overlap on the same region of the target.

The energy deposition in the target is calculated using the EGS4[2] photon energy deposition code. The code calculates the volumetric rate of energy deposition as a function of axial and radial position along the beam trajectory.

The temperature response of the target due to the energy deposition is calculated with the LLNL three-dimensional finite element heat transfer code, Topaz3d[3].

The structural response of the target is calculated with the LLNL finite element structural analysis code, Nike3d[4], which calculates the thermal expansion of the material using a coefficient of thermal expansion and the temperature change calculated by

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[1] Lawrence Livermore National Laboratory, Livermore, California.
[11] Stanford Linear Accelerator Center, Stanford, California.

Topaz3d. Stresses are calculated from relations of titanium material properties of stress and strain.

TARGET GEOMETRY

The Tesla target, figure 1, is a rotating wheel, of titanium alloy, with a thickness of 1.42 centimeters and a radius of 0.8 meters. The wheel is assumed to be rotating with a peripheral speed of 50 meters/second (600 RPM).
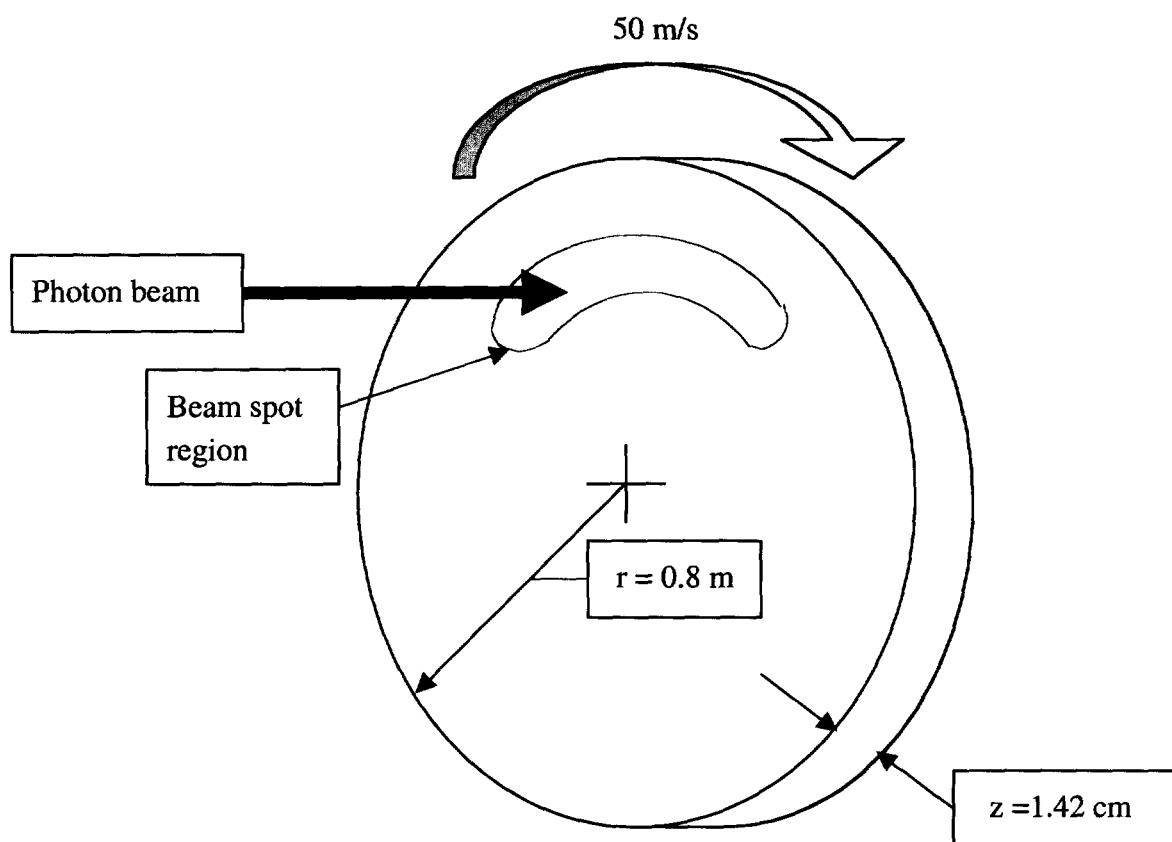
Figure 1. Target wheel schematic

PHOTON BEAM ENERGY DEPOSITION

The Tesla photon beam is produced using a K=1 undulator. The cutoff energy for the first harmonic radiation is 28 MeV and the average photon energy is 22.2 MeV. The full photon spectrum is used to calculate the energy deposition. The beam consists of 2820 bunches per pulse, spaced 337 ns apart, with a pulse frequency of 5 hertz. The beam has a spot size radius of 0.75 mm.

The energy deposition in the target is determined from the electromagnetic shower effect occurring as the photons pass through the titanium target[5]. The EGS4 electromagnetic shower code was used to model the problem and figure 2 shows results for energy deposition per gram of material as a function of radius and distance into the target. The target was modeled with eight regions in the axial direction, with K=1 representing the first region as the beam enters the target and K=8 representing the last or back region of the target. The target is 0.4 radiation lengths thick (1.42 cm).

Energy Deposition in Ti from Incident Undulator Radiation

$K_u=1$
$E_{c10}=28$ MeV
$\sigma_{xin}=\sigma_{yin}= 0.75$ mm
0.05 r.l. per K slice
100,000 γ per run
7 run average
9.58 J per incident bunch

Figure 2. Energy deposition (J/g) in the titanium target[5] as a function of radius
from the beam axial centerline, and axial distance for eight
regions from the front (K=1) to the back (K=8).

The individual bunches will overlap their energy deposition as the target rotates. Figure 3 shows that the maximum energy deposition is above 200 J/g.
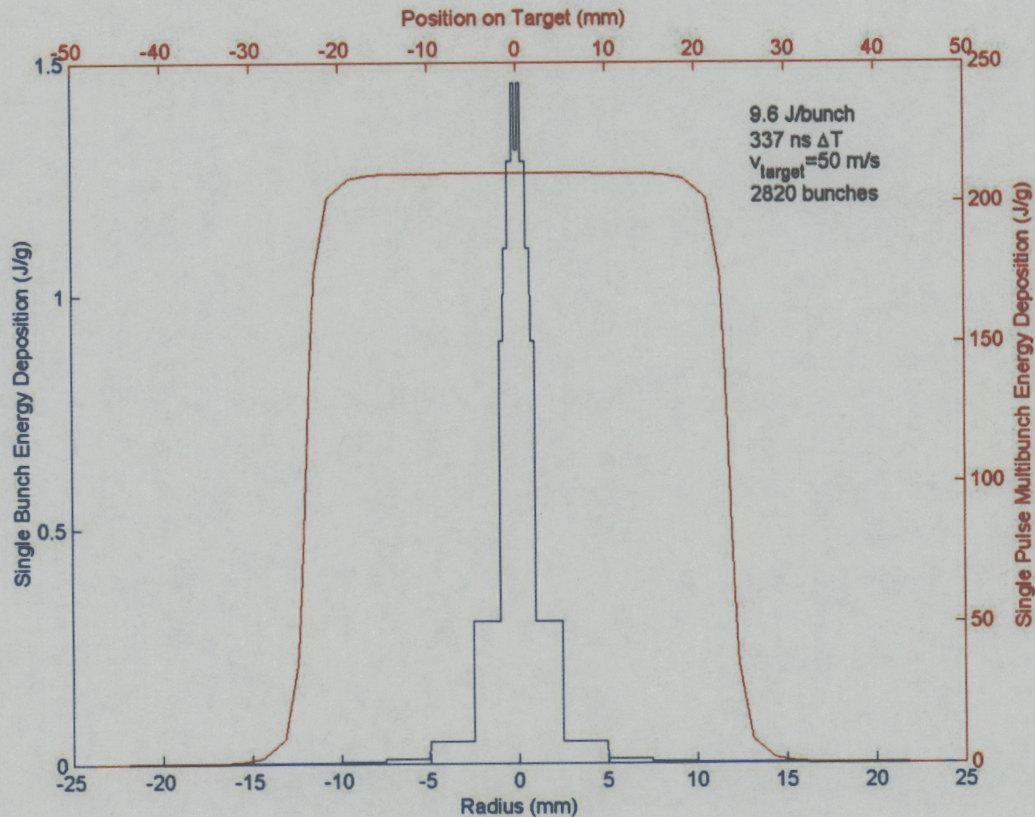
Figure 3. Peak energy deposition for the single bunch (blue) and over the pulse train[5] (red).

THERMAL ANALYSES

The temperature profile in the target is modeled with an energy per unit volume heat source. The heat source mimics the Gaussian radial profile and axial profile shown in figure 2 and the energy source is input as a moving heat source at a velocity of 50 m/s.

From material properties of density, specific heat, and thermal conductivity and the volumetric energy deposition rate, the temperature of the material is calculated. The time scale for the energy deposition (1 millisecond) is relatively small versus the time for any energy to conduct into the surrounding material. The temperature profile that exists in the material initially after 1 millisecond of pulse energy deposition is thus the profile that is used to determine the resultant material thermal stress. Over a time scale of seconds, the temperature and stress relax to low values until another pulse strikes the same region.

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Material thermal properties assumed for the titanium alloy are given in table 1.

Table 1. Typical Titanium alloy thermal properties

Property	Density, Kg/m³	Specific heat, J/Kg°K	Thermal conductivity, W/m°K
Value	4,500	530	21

The energy deposition results in an elongated spot on the target that heats up from an initial assumed temperature of 30 °C to a peak value of 471 °C. Figure 4 shows the back side of the target with a temperature profile after 0.2 milliseconds of beam pulse duration.
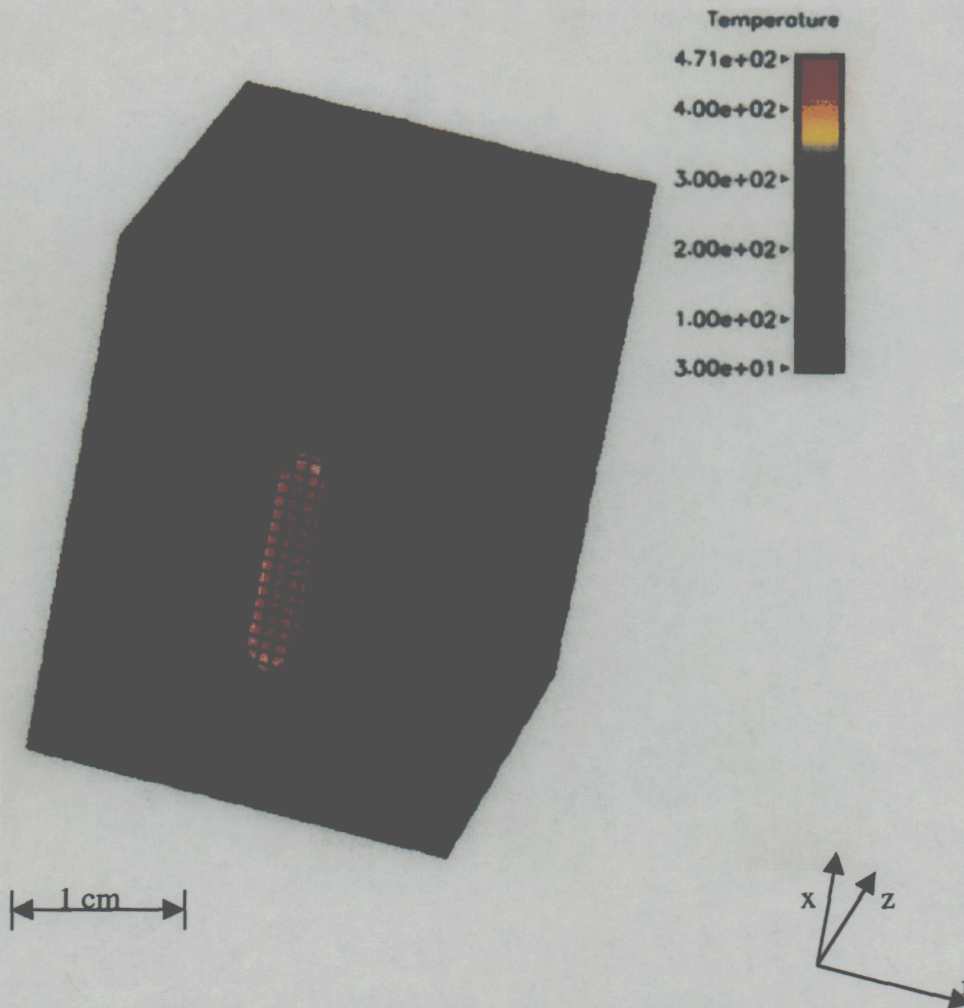

Figure 4. Temperature profile, °C, after 0.2 ms.

The temperature profile in cross section is shown in figure 5. The figure shows that the peak temperature is obtained only after the wheel has rotated enough to allow for overlap of the bunch energy deposition in a similar manner as in figure 3.
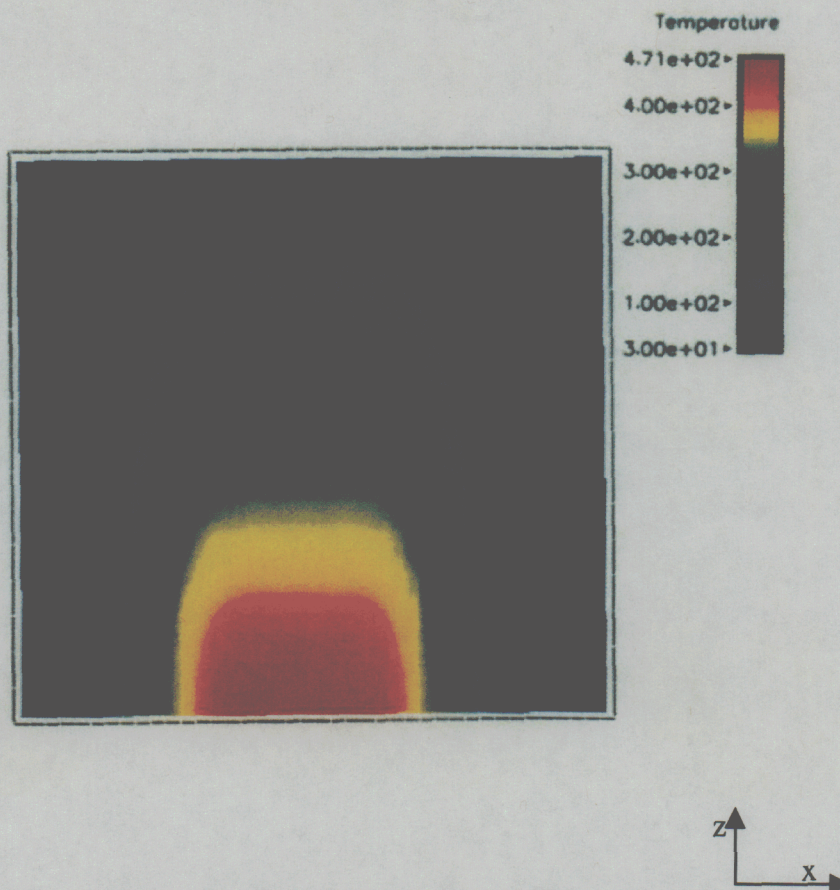

Figure 5. Target temperature, °C, cross section after 0.2 ms.

STRUCTURAL ANALYSES

The heating of the target results in thermal expansion of the heated target material. The stresses resulting from the expansion are calculated using the LLNL three-dimensional finite element structural mechanics code, Nike3d, with temperature input from the results of the Topaz3d thermal analyses. The Nike3d code calculates the thermal expansion by use of a coefficient of thermal expansion and a change in target temperature. Stresses are determined from stress and strain relationships for the titanium material. For these analyses, a linear elastic material model is assumed.

The problem is modeled over a small rectangular portion of the target that includes the region that a beam pulse impinges upon. Figure 6 shows the effective stress along the back side of the target as the beam traces out a path on the target. The stress is initially low as the beam pulse first strikes the target and as beam pulse bunches overlap

the stresses increase to a maximum value of 38 Ksi ($2.68 \times 10^{+8}$ Pa). This maximum value remains steady as the beam continues to trace a path on the target until the pulse is completed and stresses drop. The effective Von Mises stress is a correlation of the stress components in the part that can be compared to material yield and strength properties. The material yield strength of typical alpha-beta titanium alloys at high temperatures of 470 °C is in the range of 90 to 110Ksi (6.2 to 7.6 $\times 10^{+8}$ Pa).
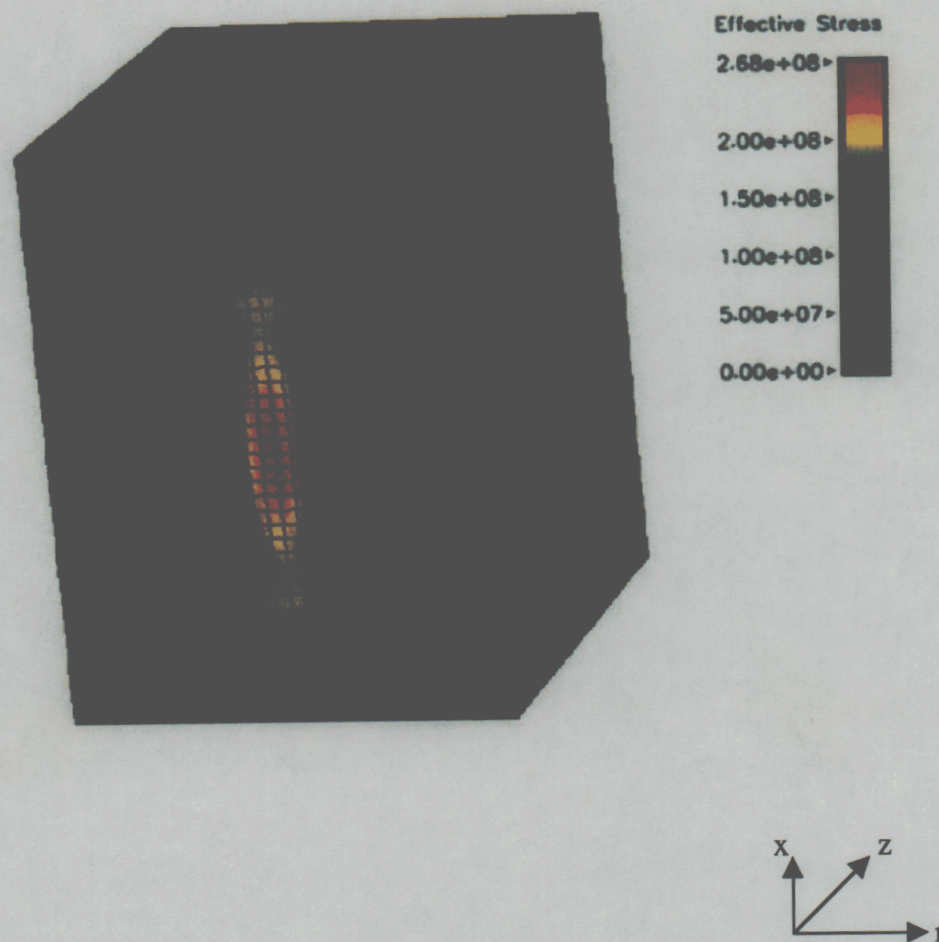

Figure 6. Effective stress (Pa) due to one beam pulse.

Structural properties assumed for the alpha-beta titanium alloy are given in Table 2. The alpha-beta titanium material contains a few percent of other elements such as aluminum, and iron.

Table 2. Titanium alloy structural properties.

property	Young's modulus, Psi (Pa)	Thermal coefficient of expansion, $°C^{-1}$	Poisson's ratio
Value	15×10^6 ($1 \times 10^{+11}$)	9×10^{-6}	0.3

SUMMARY

The above analyses presented information as to energy deposition in a target due to an impinging photon beam. The resultant thermal stress due to the thermal expansion of the target material is relatively low and about 0.3 of the material yield strength. Due to the cyclical nature of the beam pulses and the target stress, the material fails at a fatigue stress that is some fraction of the yield stress. Generally stresses below one third to one half of the yield stress may be considered adequate to avoid fatigue failure. For our case, the stresses are well below yield stress and low enough to avoid fatigue failure.

Other considerations that may affect target performance is radiation damage of the material due to the high energy photons impinging on the target and causing dislocation defects. The defects may cause brittleness in the material and may lead to lower fatigue failure stresses. One way to avoid this problem is to design the target so that the beam exposure per unit volume of material is kept low and below normal radiation damage exposure levels.

REFERENCES

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